USAARL Report No. 88-14

The Combat Emergency Medicine Expert System (CEMES): Project Phase II Report

By

Douglas E. Landon
Glenn M. Mitchell

Biomedical Applications Research Division

August 1988

United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama 36362-5292

Notice

Qualified requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Cameron Station, Alexandria, Virginia 22314. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

Reviewed:

Gerald P. Krueger

GERALD P. KRUEGER, Ph.D.,
LTC, MS
Director, Biomedical Application
Research Division

Released for publication:

David H. Karney

J. D. LaMOTHE, Ph.D.
COL, MS
Chairman, Scientific
Review Committee

DAVID H. KARNEY
Colonel, MC
Commanding

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAARL Report No. 88-14	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Aeromedical Research Laboratory 6b. OFFICE SYMBOL (*If applicable*)	7a. NAME OF MONITORING ORGANIZATION U.S. Army Medical Research and Development Command
6c. ADDRESS (*City, State, and ZIP Code*) P.O. Box 577 Fort Rucker, AL 36362-5292	7b. ADDRESS (*City, State, and ZIP Code*) Fort Detrick Frederick, MD 21701-5012
8a. NAME OF FUNDING / SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (*If applicable*)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (*City, State, and ZIP Code*)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62787A	3E161 787A879	BI	167

11. TITLE (*Include Security Classification*)
The Combat Emergency Medicine Expert System (CEMES) Project: Phase II Report

12. PERSONAL AUTHOR(S)
Landon, Douglas E., and Mitchell, Glenn W.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (*Year, Month, Day*)	15. PAGE COUNT
Final	FROM _____ TO _____	1988 August	52

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (*Continue on reverse if necessary and identify by block number*)
FIELD	GROUP	SUB-GROUP	Artificial intelligence, expert system, medicine, medical automation, robotics
12	09		
06	05		

19. ABSTRACT (*Continue on reverse if necessary and identify by block number*)

The exploratory development of a Combat Emergency Medicine Expert System (designated CEMES) has been conducted. This report outlines the project's rationale and documents the major design concepts underlying the exploratory development of CEMES. CEMES is an expert system designed to perform automatic diagnosis and treatment of hemorrhagic shock with or without concurrent chemical agent contamination. Its anticipated use is as a forward-area medical aid, operating automatically following initial hands-on first-aid and system attachment by a medic, medic extender, or physician. A laboratory prototype CEMES has been designed and developed as a totally self-contained, closed-loop system. It monitors vital signs through noninvasive sensors and determines a diagnosis through vital sign analysis. It analyzes medical trends based on diagnostic and vital sign changes, and both warns for and guards against catastrophic or gradual deterioration in casualty condition. CEMES advises personnel as to when to initiate IV or drug delivery line, and then automatically manages IV fluid infusion

(Continued)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☑ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (*Include Area Code*)	22c. OFFICE SYMBOL
Chief, Scientific Information Center	(205) 255-6907	SGRD-UAX-SI

Block No. 19. Abstract (Continued)

and periodic or continuous drug treatments based on current diagnosis and trends. CEMES monitors its own logistical status, advising as to when IV fluid is getting low and bag replacement is necessary. In addition, the logistical analysis watches for inoperative or malfunctioning sensors to facilitate degraded mode operation. CEMES also maintains a diagnostic and treatment history for examination by a physician at a definitive care facility. A color graphics display is used to present system information. Sensor data is simulated through off-the-shelf patient simulators and custom-designed simulation equipment. IV fluid infusion treatment is simulated using small pumps, colored water, and actual IV line tubing that delivers fluid at the rates prescribed by CEMES.

Table of contents

List of tables

Introduction

Overview

This is the phase II report documenting the combat emergency medicine expert system (CEMES) project. The work presented in this report covers the complete exploratory development of CEMES conducted from November 1985 to April 1987. The CEMES project is the core effort within the artificial intelligence research program being conducted at the U.S. Army Aeromedical Research Laboratory.1

The theoretical background and feasibility analysis for the CEMES project was completed in September 1985 under the In-House Laboratory Independent Research (ILIR) program and documented in Landon (1986). The feasibility study outlined the concept development underlying the CEMES project in addition to providing a general review of artificial intelligence and existing medical expert systems. Two previous reports (Landon, 1987a, 1987b) documented the CEMES project at the completion of Phase I as interim progress reports.

The CEMES project is documented in three separate reports. This report outlines the rationale, general operation, and final design concepts underlying the CEMES system and project. A second report (Landon, 1987c) documents the CEMES programs, program code, and other specifics of CEMES construction. The second report exists primarily for archival purposes and is not required for reference when reading this report.

Military relevance

Army 21 operational doctrine anticipates a complex, fluid, and chemical, biological, and/or radiological (CBR) contaminated battlefield expected to produce mass casualties. The expertise of physicians and other medical personnel will be needed at all battlefield levels to reduce medical complications and prevent avoidable deaths. However, the nature of the battlefield and anticipated lack of numerical superiority in both land and air

---

1 DD Form 1498, Artificial Intelligence and Robotics: Biomedical Applications, Project Number 3E16277A879, Work Unit Number 167. Protocol titled "Investigation and Exploratory Development of Medical Expert Systems for Military Applications" dated 22 March 1985 and approved 19 July 1985.

forces may prevent quick and efficient casualty evacuation. Rapid and expert care will be necessary for casualty survival and potential return to duty. Lack of personnel will make it unfeasible to assign the required numbers of physicians at all battlefield levels as necessary to provide the appropriate medical care. In addition, casualties among medical personnel would aggravate the effects of mass casualty situations.

The Medical Systems Program Review (Robertson and Glazier, 1985) outlined a new battlefield medical care strategy. This strategy included a continuum of care from the forward line to the continental United States. A casualty would "flow" through the continuum only so far as his injury(s) dictated and then he would be returned to duty as soon as possible. Combined with the continuum of care was the idea of far forward care, where first aid and trauma care would be administered as far forward in the continuum of care as possible. Technological advances in emergency medicine would enhance the implementation and effectiveness of the continuum and far forward care concepts.

Artificial intelligence has been designated as one of the Army's major research and development thrust areas,[2] with artificial intelligence-based medical systems a major subarea.[3] Although medical expert systems have been developed and used for academic research, there have been few attempts at developing this technology for military medical applications. The likelihood of successful attainment of the medical and health care mission could be enhanced through artificial intelligence systems that both diagnose and treat casualties. In addition, a properly designed and implemented medical expert system could bring to the battlefield health care capabilities currently available only from specialists in rear echelon facilities. Such systems also could serve as aids to physicians during peacetime.

---

[2] The Militarily Critical Technologies List, Office of the Under Secretary of Defense, Research, and Engineering, Washington, D.C., October 1985, paragraph 1.3.3.

[3] Combat Service Support Mission Area Analysis - Level II, Vol 1: Executive Summary, January 1983, pages 14a-14b, paragraph 15. Also see the study on artificial intelligence by the National Research Council (1983).

System concept

Background

Artificial intelligence (AI) is a term used to refer to the discipline within cognitive science devoted to the attempt to program computers to perform tasks usually thought of as requiring some measure of intelligence (indicated by a human's unique ability to accomplish the same task). General research in AI has resulted in the technological capability for producing limited domain, but sophisticated, problem solving programs. These programs are known collectively as expert systems because they attempt to duplicate or emulate human expert abilities within some well-defined domain.

The specific design and implementation of any particular expert system is unique to that system. The technical aspects of general expert system design were reviewed in the CEMES feasibility study (Landon, 1986). The specific aspects of CEMES' preliminary design were covered in the Phase I interim reports (Landon, 1987, Landon, 1988a). The final design and operation of CEMES is documented in this report.

CEMES medical domain of operation

CEMES task domain is emergency medicine diagnosis and treatment of casualties with respect to hemorrhagic shock and chemical agent contamination prior to receiving definitive care. That is, CEMES is designed to provide limited casualty care management with the goal of reducing morbidity rates due to hemorrhage and shock. The importance and critical nature of hemorrhage and shock with respect to the morbidity rate of casualties was pointed out by Bellamy (1984) in an analysis of the causes of death in conventional land warfare:

> "First and foremost, there is a need to improve the field management of hemorrhage. The combination of simple first aid measures plus infusion of an oxygen-carrying solution and/or use of pharmacologic interventions designed to optimize cardiac output (anti-shock drugs) might be lifesaving in a surprisingly large number of casualties." (pg. 61)

The primary objectives in emergency medicine are resuscitation and stabilization pending a complete diagnosis and determination of disposition at a definitive care facility. Initial resuscitative measures and battlefield first aid must be accomplished by the platoon medic, medic extender, or a physician. The extensive hands-on requirements for first aid measures preclude the use of an automated system (i.e., although great advances have occurred in robotics, a robotic hand with the sensitivities and

dexterity of the human hand has yet to be devised). However, once a casualty is attached, an automated system could provide limited aid to a physician or medic in any future resuscitative measures that might be required.

CEMES military operational requirements

The prevalent operational environment for CEMES is dictated by military requirements. Following military doctrine (Department of the Army, FM 100-5, FM 8-10; Cook, 1984; Robertson and Glazier, 1985), several operational and environmental assumptions that have governed the design of CEMES are:

1. The system should be capable of operating within a CBR contaminated battlefield, requiring diagnosis and treatment of CBR contaminated casualties.

2. Expendable supplies (e.g., IV fluid) may be extremely limited, placing a high value on economy of supply use and efficient treatment strategies.

3. Qualified maintenance personnel may not be present, requiring the system to be self-diagnosing to compensate for damaged or inoperative subassemblies (i.e., degraded mode operation).

4. Immediate casualty evacuation will not necessarily be available, requiring long-term casualty care up to 48 hours.

Although the above four operational assumptions are not exhaustive, they cover the major aspects of design that are somewhat unique to the military. The implications of these requirements for CEMES' design were examined in the feasibility study (Landon, 1986).

It is anticipated that CEMES could be deployed as far forward as the battalion aid station. A CEMES unit could function in a multicasualty mode, where a single CEMES system monitors several casualties, or in a single casualty mode, where each casualty has a unique CEMES unit. The latter case is more likely. That is, a single casualty, battery-operated CEMES unit could be incorporated into a stretcher or other suitable transport device and be evacuated with the casualty until definitive care is reached. Add-on modules could provide increasingly sophisticated medical capabilities as the casualty moves through the evacuation system, possibly to the point of providing the casualty with his own personalized mobile critical care unit.

Outline of CEMES operation

The central design principle underlying CEMES is that of being a totally self-contained, closed-loop system. For this purpose, closed-loop expert systems were defined as systems that require little or no human intervention to accomplish their objectives (Landon, 1986). For an emergency medicine expert system, this implies that both diagnosis and treatment of emergency medical conditions is accomplished by the expert system. Therefore, strict closed-loop operation requires the system to operate in the absence of, or in lieu of, an attending physician, although a human assistant will be needed to attach biomedical sensor/treatment equipment and replace expendable supplies. However, CEMES was designed to be more of a sophisticated medical assistant, decreasing physician or medic workload by having some elements of autonomy and not requiring continuous human interaction.

The closed-loop aspect of CEMES operation is implemented in a process control loop (which will be explained more completely in the section "The CEMES expert system"). To provide a preliminary overview, the major processing events in the CEMES' closed-loop cycle are:

1. CEMES first obtains vital sign data automatically through noninvasive biomedical sensors attached to the casualty. A preliminary analysis is conducted to determine if the data is valid (e.g., within acceptable human physiological limits). In addition, an attending medic or physician can indicate whether or not chemical agent contamination is present or suspected. This design consideration aids in workload reduction by not requiring attending personnel to continually be available for data entry to the system.

2. Following data collection, CEMES determines a diagnosis with respect to shock and/or chemical agent contamination and determines a preliminary treatment recommendation based on the diagnosis. CEMES treatments are limited to IV fluid infusion and atropine drug injections administered intravenously through the IV line. The final IV infusion rate and atropine dose is determined later in the cycle.

3. Following the diagnosis, CEMES examines the casualty's vital sign history for trends. The trend analysis can have three directions (improving, deteriorating, or unchanging) and two magnitudes (catastrophic and gradual) for a total of five trend outcomes.[4] Trends are established both by examining directionality of vital signs over time and by relationships between consecutive diagnoses over time. For example, class three hemorrhagic shock obviously is worse than class one hemorrhagic shock, and so a

---

[4] The unchanging trend direction has no magnitude.

casualty that jumps to class three shock directly from class one shock is deteriorating rapidly. CEMES recognizes these relationships and takes appropriate actions based on them.

4. Prior to determination of a final treatment regimen, a logistical analysis is completed to determine IV fluid and line status, the amount of fluid remaining, and anticipated fluid need based on preliminary treatment recommendations. For example, the preliminary treatment recommendation may require IV fluid infusion when no IV line has been established. The logistical analysis recognizes this potential problem, provides the necessary messages to the medic or physician to establish an IV line, and inhibits other CEMES systems from assuming that an appropriate treatment is being administered until an IV line has in fact been established.

5. CEMES concludes an operation cycle by establishing a final treatment (i.e., IV fluid infusion rate and/or atropine dose), updating the medical history, and providing the appropriate signals to the biomedical hardware to effect the actions CEMES has determined are necessary. CEMES then recycles after a 1 minute real-time interval.

CEMES general design

Conceptual organization

The conceptual organization of CEMES is shown in Figure 1. CEMES is organized around a blackboard (Erman and Lessor, 1975; Hayes-Roth, 1985) which is a shared data structure accessible to all of the CEMES subsystems. The core of CEMES consists of the management, logistics, trend, diagnostics, and treatment subsystems. These five subsystems comprise the main expert system responsible for governing CEMES' operation. They are directly analogous to the knowledge sources used in standard blackboard-based expert systems, obtaining input from and recording output on the blackboard. These five subsystems are responsible for completing the diagnosis, constructing the IV-based treatment regimen, watching for trends, and managing the general operation of the entire system. These five subsystems and their operation as an expert system will be explained in depth in the section "The CEMES expert system."

The sensor and effector subsystems are separate both physically and logically from the core expert system subsystems. The sensor subsystem includes the necessary hardware and software for sens-

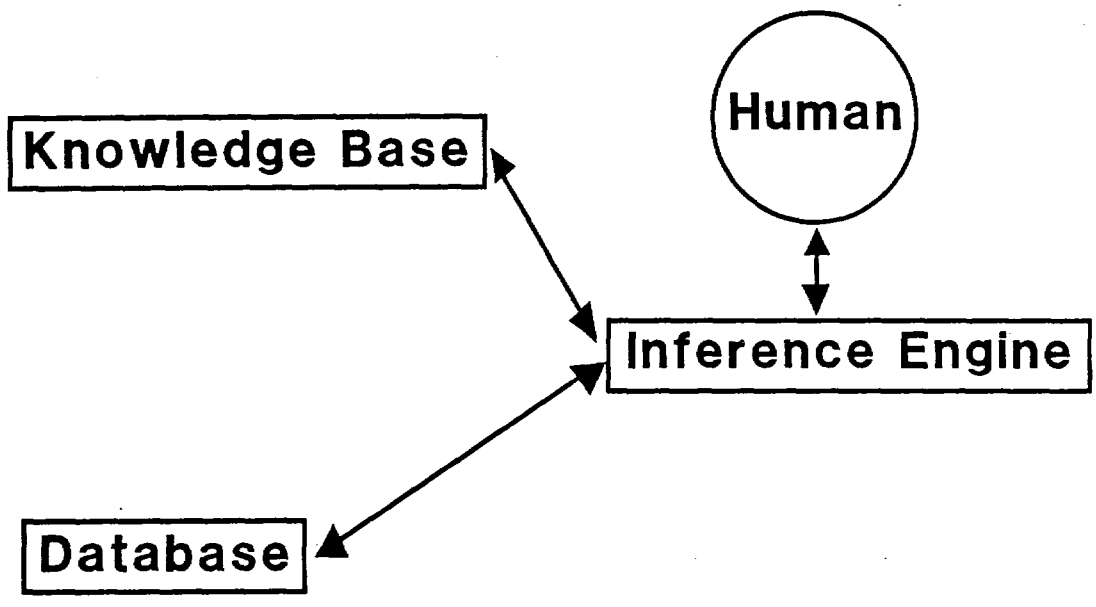

Figure 1. CEMES conceptual organization.

ing and translating biomedical signals into a numerical form suitable for analysis by the core expert system. Some of this technology now is available using off-the-shelf medical equipment. The available equipment usually includes the necessary algorithms for translating the raw signals into some standard or useful form along with a capability for sensing improper transducer attachment and simple malfunctions. The analysis of the validity of the sensor data is accomplished by the core expert system.

The effector subsystem consists of the appropriate hardware and software to govern electronically controlled IV fluid administrators. Its primary function is as a delivery mechanism for the IV-based treatment regimens. This type of equipment usually includes capabilities for sensing blockages and other malfunctions in IV fluid delivery. The operation of the sensor and effector subsystems will be explained in depth in the section "The CEMES front-end."

Laboratory equipment[5]

The exploratory development of CEMES was conducted using a Hewlett-Packard (HP) 9000, Model 520, general purpose minicomputer with the HP BASIC operating system, and a Symbolics 3640 standalone LISP machine with the Symbolics LISP operating system. Figure 2 provides a diagram showing the relationship between these computers, various other CEMES equipment, and the CEMES subsystems shown in Figure 1.

The core expert system portion of CEMES is programmed in LISP on the Symbolics 3640 LISP machine. The LISP language was selected due to its close connection with artificial intelligence development and the object-oriented programming style. The sensor and effector front-end subsystems were programmed in BASIC on the HP 9000 minicomputer to facilitate real-time input/output and signal processing operations. In addition, the HP 9000 provides the operator interface functions and the necessary communications capabilities for the CEMES' color graphic display.

An HP 6942A multiprogrammer was used to provide the required analog-to-digital, digital-to-analog, and other hardware and software functions for interfacing the vital sign simulation equipment and IV pumps to the CEMES computers. A Bio-tek Lionheart Model MPS-I multiparameter simulator, a Dynatech Model 211A patient simulator, and some custom-built equipment provided simulation capabilities for the sensor subsystem. Two FMI Model QA 600 laboratory general purpose pumps provided IV fluid infusion

---

[5] A list of manufacturers is provided in Appendix A.

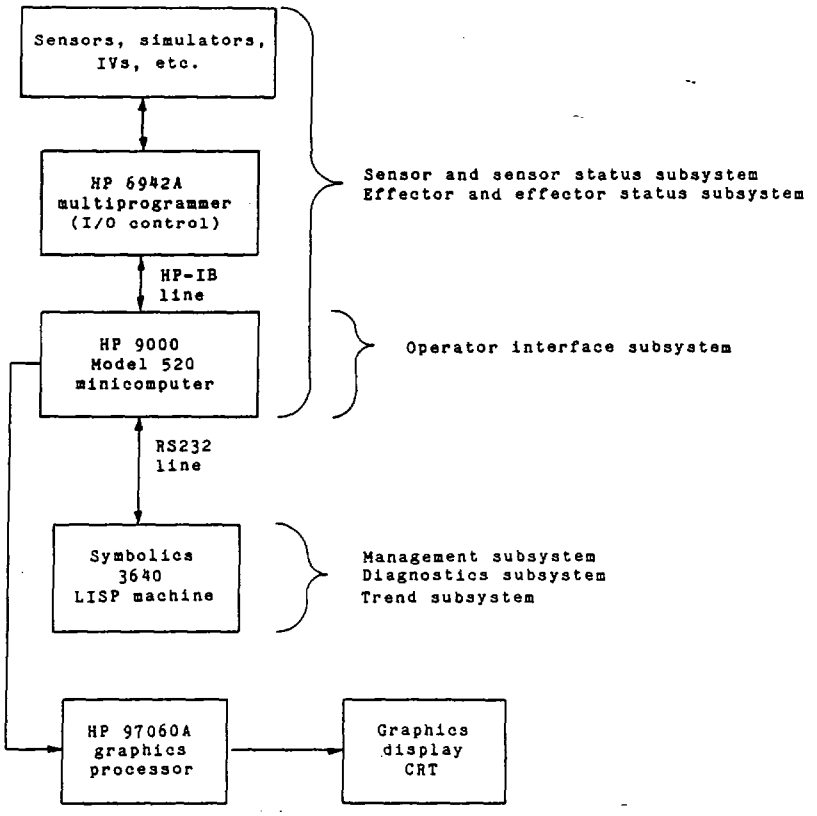

Figure 2. Laboratory equipment and CEMES subsystem relationships.

simulation capabilities for the effector subsystem. The wiring and circuit diagrams for the front-end equipment are provided in Landon (1988b).

Detailed design chart and design methodology

Detailed organizational master charts of CEMES are provided in Figures 3a and 3b. The charts in Figures 3a and 3b break down CEMES' organization in terms of equipment, subsystem, subsystem communications and information flow, and central aspects of the programming design of each subsystem. The actual flow charts and code for each subsystem are documented in Landon (1988b). The charts in Figures 3a and 3b diagram relationships and design details to aid in the explanation of CEMES' design and operation in the following sections.

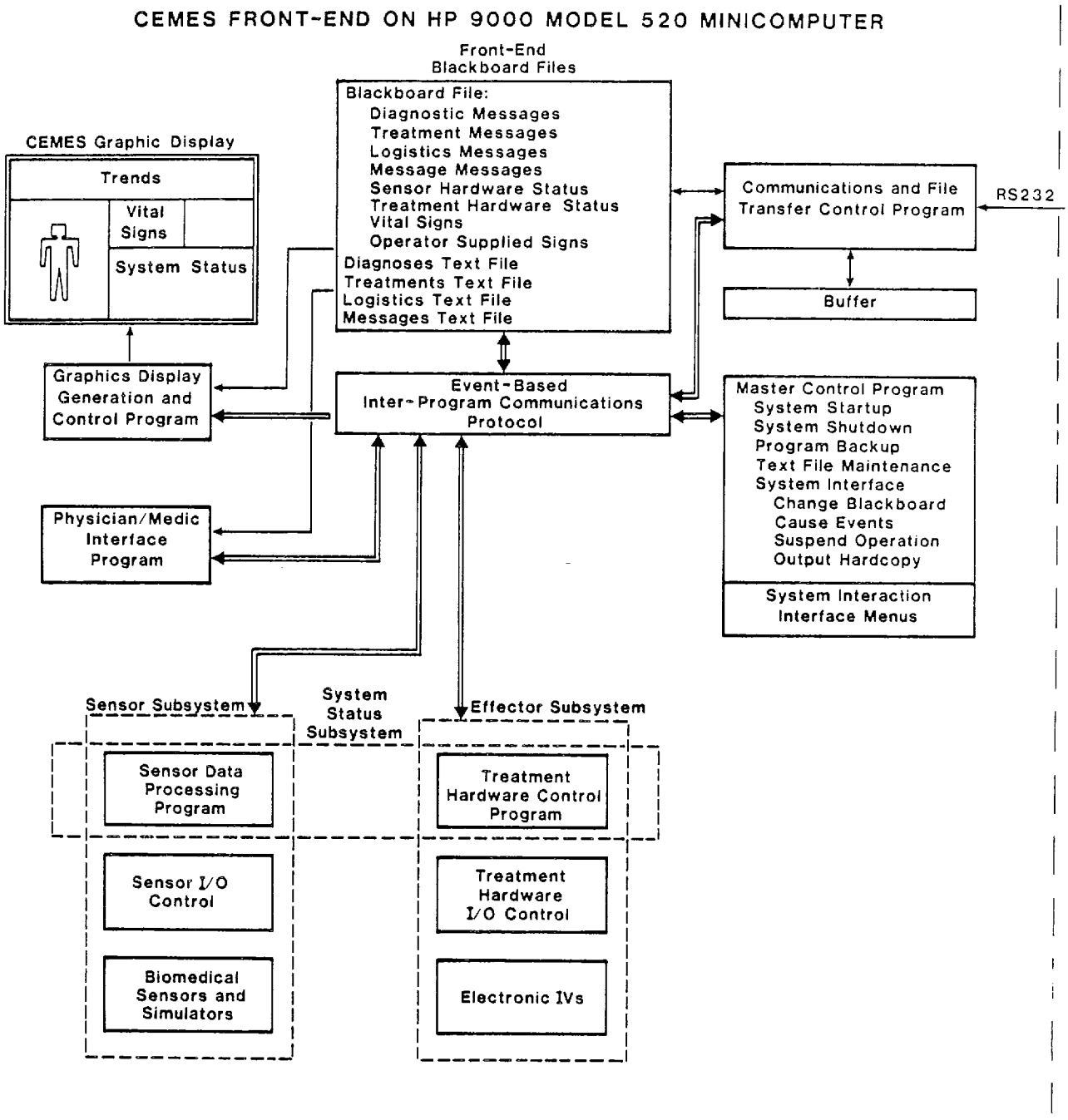

Figure 3a. CEMES front-end detailed organizational chart.

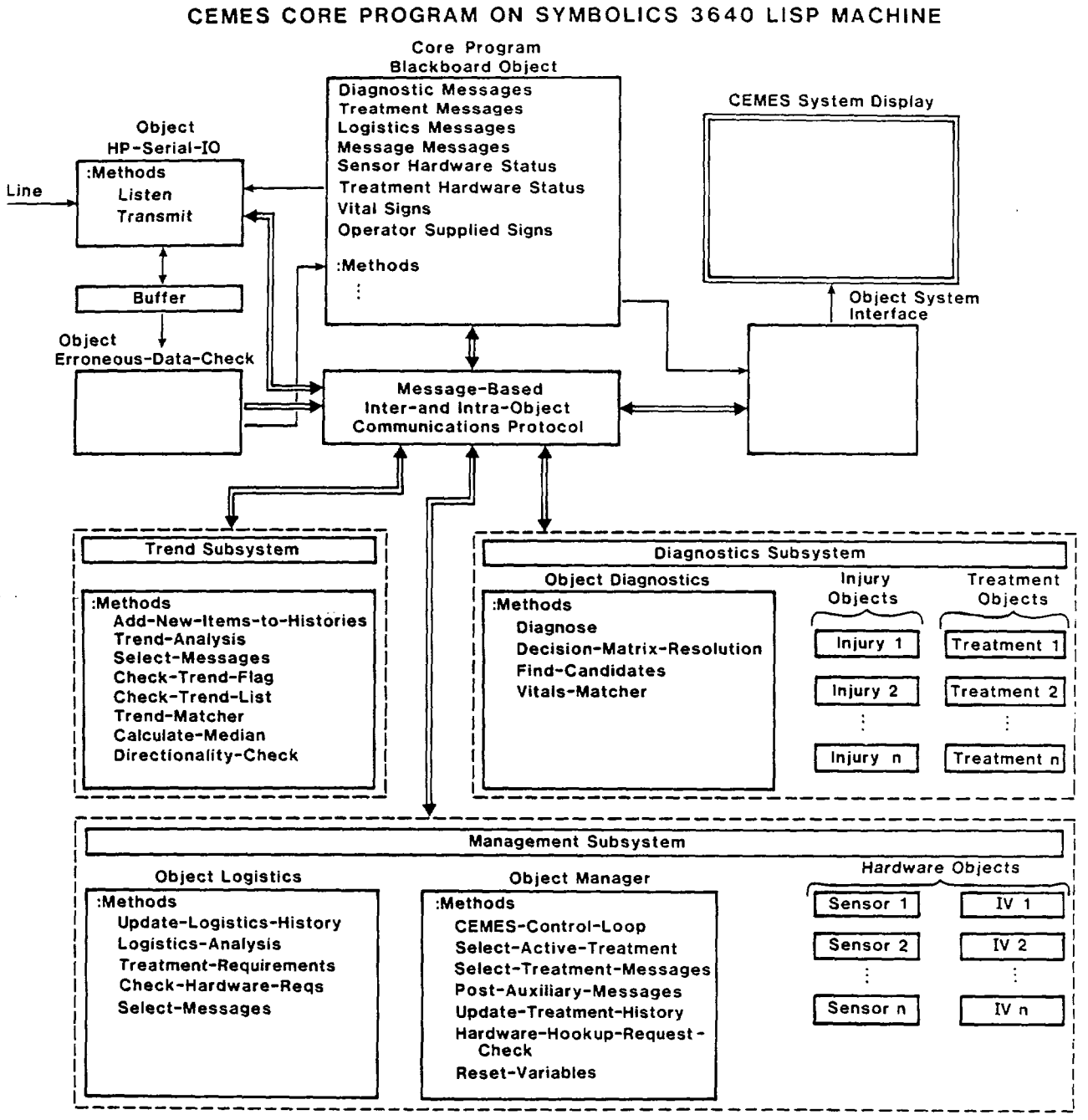

Figure 3b. CEMES expert system detailed organizational chart.

The double lines and arrows in Figures 3a and 3b represent communications capabilities and directions between subsystems within each computer. The single lines and arrows represent communications and data flow between the two computers and the operator. Note that the connection between the two computers is via a RS232 line, a portion of which appears in each figure. This separation is necessary because the double lines represent communications implemented differently than the communications represented by single lines. Communications represented by double lines are not accessible to the operator during normal operation of the CEMES system.

The double-lined communications also represent the object-oriented programming style used for CEMES development. This style involves programming in terms of independent chunks, or objects, that directly correlate with the major aspects and divisions of the programming problem (see Stefik and Bobrow, 1986). This division is straightforward with CEMES, each subsystem being programmed as its own object or collection of objects.

The LISP language implementation on the Symbolics 3640 provides direct object-oriented programming constructs. The communication protocol used between objects is referred to as message passing. Therefore, the subsystem objects programmed on the Symbolics 3640 use a message-based inter- and intra-object communications protocol. However, the BASIC language implementation on the HP 9000 does not provide for a direct object-oriented programming style. It is a multitasking language which was used to simulate the features of object-oriented programming. This was accomplished by coding an object as an independent program and using the event semaphores provided by the HP BASIC language for message passing.[6]

It is important to note that a blackboard appears in both Figures 3a and 3b. The core program blackboard object appearing in the Symbolics 3640 portion of CEMES (i.e., Figure 3b, the actual expert system portion) represents the blackboard shown in the general design in Figure 1. The blackboard shown for the HP 9000 programs (Figure 3a) is a duplicate with some additional data files. This type of design was selected to facilitate the speed and efficiency of communications between the subsystems on the two computers and avoid a potential bottleneck that might

---

[6] Event semaphores generally are used to signal control or availability of shared devices in multitasking environments. For example, two programs running concurrently may need to use a single device such as a printer. Since both programs cannot access the printer concurrently, a semaphore is used as signal between the programs to indicate the availability of the shared printer.

degrade real-time operation. The communications programs for each computer maintain congruency between the two blackboards by transmitting only those data required or changed. The scheduling of the communications is controlled by the expert system portion of CEMES on the Symbolics machine.

The CEMES expert system

The process control loop and subsystem taskings

The primary operational portion of CEMES is the expert system that resides on the Symbolics 3640 LISP machine. As noted in the previous section, the CEMES expert system is composed of the management, logistics, trend, diagnostics, and treatment subsystems (Figures 1 and 3b) that act as independent knowledge sources with the blackboard serving as a shared data repository. However, CEMES does not use a dynamic blackboard control strategy (see Hayes-Roth, 1985). In a dynamic blackboard-based expert system, each knowledge source operates independently based on the information on the blackboard. Knowledge sources generate activation records which are prioritized for completion by a scheduling mechanism. Therefore, the order of processing knowledge source activation records changes with and in response to the contingencies generated by the problem.

CEMES, however, uses a solution-based strategy realized in a process control loop that activates each knowledge source (i.e., subsystem) at the appropriate time when its task must be completed. In addition, the CEMES blackboard is unidimensional in that it consists of levels of abstraction containing "raw" data (vital signs), intermediate results (system status data), and final results (diagnoses and display messages). There is no time, solution interval, or other second dimension as is often the case for systems based on a blackboard control architecture.[7]

The process control loop is relatively straightforward and largely based on the requirements for medical diagnosis and treatment (from Landon, 1986). The process control loop is diagrammed in Figure 4. It should be noted easily that the subsystem organization in terms of objects (Figure 3b) directly corresponds with the principal steps of the process control loop (Figure 4). This reflects the object-oriented programming style and maintains a direct and visible relationship between program function and code structure. Each step in the process control loop will be explained along with the tasking assignments of the various subsystems for each step in the loop.

CEMES first obtains the necessary biomedical data through the front-end sensor subsystem. The front-end sensor subsystem has design for both stimulating automatic biomedical sensor equipment and entering vital sign data through a menu-driven program. The specific operation of the front-end sensor will be covered in detail in the section "The CEMES front-end." It should be noted

---

[7] Conversely, the solution interval dimension is irrelevant because the process control loop executes the actions of the various subsystems in a strict order.

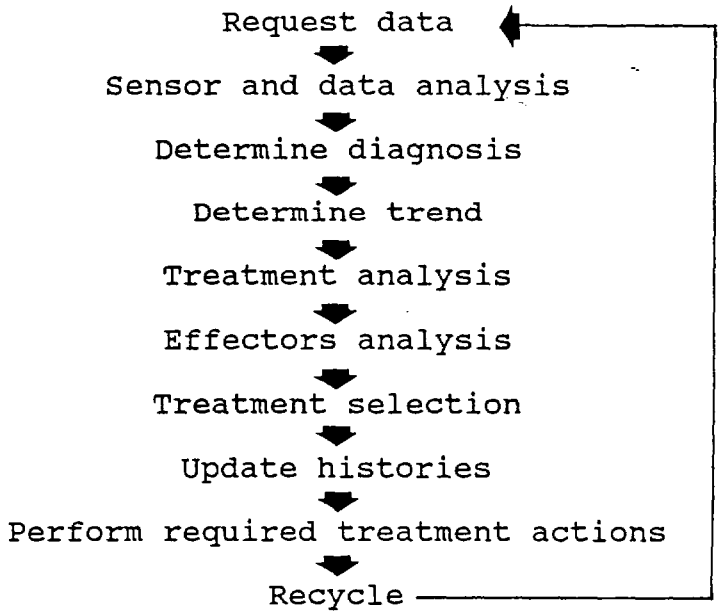

Figure 4. CEMES expert system process control loop.

that vital sign data currently are limited to blood pressure, pulse pressure (the difference between systolic and diastolic blood pressure), pulse, and respiration rate (i.e., the key vital signs for hemorrhagic shock).

Following data collection, the logistics subsystem determines whether or not the new vital sign data is valid. This involves a straightforward analysis of the vital signs with respect to physiological range limitations (e.g., a pulse of 400 is invalid) and consistency (e.g., diastolic BP should not exceed systolic BP). Whatever vital signs, if any, that are found to be invalid are so marked on the blackboard and not used by subsequent analyses.

The next, and principal, step is for the expert system to determine a diagnosis with respect to shock and/or nerve agent contamination (or to indicate if the casualty is stable, should that be the case). The diagnostics subsystem is tasked with completing this step. The diagnostic inference procedure, to be explained later, uses whatever data is available after validation by the logistics subsystem. The diagnostics subsystem also retains all knowledge representations of the various possible diagnoses of shock and contamination. The form of these representations will be covered in the following subsection.

The fourth step is for the trend subsystem to determine a diagnostic trend. This is accomplished both by examining relationships between successive diagnoses and analyzing the vital sign history of the casualty. The trend analysis can have three directions (improving, deteriorating, or unchanging) and two magnitudes (catastrophic or gradual) for a combined total of five trend outcomes (i.e., the unchanging direction has no magnitude). The trend subsystem also maintains a medical history that includes vital sign data, diagnostic results, and trend results.

After determination of the trend, the treatment subsystem performs a preliminary analysis to determine any required treatment (consisting of an IV fluid infusion rate and/or atropine dose). The treatment subsystem uses various treatment models representing treatment parameters for fluid infusion or drug dosage. These models are attached to corresponding diagnostic representations. Therefore, the appropriate treatment model is preselected by the diagnosis. However, the selection of a final treatment regimen (derived from the model) is temporarily suspended pending a second logistical analysis of the effector subsystem.

Following preliminary treatment analysis, the logistics subsystem completes a second analysis to determine if the appropriate logistical conditions have been met for delivery of the proposed treatment regimen. If IV fluid infusion is required by the treatment analysis, then a determination must be made to see if the required equipment is available and able to administer the requested treatment. This analysis involves determining if the proper number of IV infusion units are attached, signaling the hookup of IV infusion units when required, tracking the administration and depletion of IV fluid, and providing indications for IV bag replacement as necessary. For example, the treatment model attached to the current diagnosis may require IV fluid infusion when no IV lines have been established. The effectors analysis senses this problem, provides the necessary messages to signal the medic or physician that an IV line is required, and informs the treatment subsystem so that it won't erroneously assume that the proper treatment can be administered. The logistics object uses system hardware representations to accomplish its task.

After the effectors analysis, the treatment subsystem finalizes the IV infusion rate and/or atropine dose. It writes the necessary information on the blackboard for transmission to the effector subsystem for implementation.

The process control loop is concluded by updating all medical histories in the various subsystems maintaining such accounts and providing the proper signals to effect the treatments or update

the graphics display as required. The process control loop then recycles after a 1-minute real-time interval.

The process control loop itself is mediated through inter-and intrasubsystem object-oriented message passing. The method (i.e., code) containing the control loop currently resides as part of the manager object in the management subsystem. This loop also serves as point of entry and exit for external control of CEMES on the Symbolics LISP machine.

Knowledge representation

The principal representational technique used in the CEMES expert system is the frame. Each diagnosis, treatment, and system component model is represented using a frame-based form. Each treatment model frame is attached to a complementary injury model frame, with the system component models being independent frames.

The central knowledge component in CEMES is the injury frame because it serves as the "glue" that relates the various subsystems and their taskings. The basic form of each injury frame is shown in Figure 5. The features of each injury frame include a slot holding a list of diagnostic properties, a group of slots for trend analysis, a single slot that identifies the treatment procedure for that particular diagnosis, and a slot holding an ordinal measure of severity on a range of 1 through 10. An actual injury frame for class 3 hemorrhagic shock is given in Figure 6 to provide an example of a frame with specific information entered into the various slots.

The diagnostic-property slot provides information used by the diagnostic inference heuristic for activation of the frame as the current diagnosis. Various vital signs and their ranges that indicate the injury are listed. Since only quantitative vital signs are used, a numerical range for each sign is given. The inference procedure then uses this information when determining if the frame should be activated.

The trend slots provide both property lists for trend directions and pointers that represent this injury's relationship with other injuries when such relationships exist a priori. The trend inference procedures apply this information to determine trend direction and magnitude using an algorithm to be discussed later.

```
Injury-name: <name-of-injury>
  Diagnostic-properties: ((property range) ...)
  Trends:
       Properties:
            Getting-worse:  ((property direction) ...)
            Getting-better: ((property direction) ...)
       Relations:
            Worse-than:       <name-of-injury>
            Much-worse-than:  <name-of-injury>
            Better-than:      <name-of-injury>
            Much-better-than: <name-of-injury>
       Current-direction:
            Range:   <worse,much-worse,better,much-better,
                      unchanged>
            Default: unchanged
  Treatment-procedure: <procedure-name>
  Severity-index:
       Range: <1-10>
```

Figure 5. Injury frame organization.

```
Injury-name:  Class-3-hemorrhagic-shock
  Diagnostic-properties: ((bp-sys 80-89) (pulse 121-180)
  (pulse-pressure 0-30) (respiration 29-33))
  Trends:
       Properties:
            Getting-worse:  ((bp-sys <) (pulse >))
            Getting-better: ((bp-sys >) (pulse <))
       Relations:
            Worse-than:       Class-2-hemorrhagic-shock
            Much-worse-than:  Class-1-hemorrhagic-shock
            Better-than:      Class-4-hemorrhagic-shock
            Much-better-than: None
       Current-direction: unchanged
  Treatment-procedure: Class-3-shock-treatment
  Severity-index:  8
```

Figure 6. Class 3 hemorrhagic shock diagnostic frame.

The treatment-procedure slot contains the name of the appropriate treatment model frame for the diagnosis modeled by the injury frame. The treatment models also are represented by frames in the general form shown in Figure 7. All treatment frames have the slots outlined under the "Basic frame" heading in Figure 7. The basic slots provide for a treatment procedure name and adjustments to the treatment based on the results of the

trend analysis. These adjustments have a direction (+, -) and a numerical amount in cubic centimeters per hour (cc/hr) for IV fluid and milligrams (mg) for atropine.

BASIC FRAME-

```
Treatment-name: <name-of-treatment>
  Trend-adjustments:
       Unchanged:    (direction,amount)
       Worse:        (direction,amount)
       Much-worse:   (direction,amount)
       Better:       (direction,amount)
       Much-better:  (direction,amount)
```

ADDITIONAL SLOTS FOR IV FLUID TREATMENT-

```
  Properties:
       IV-units-required:
            Range:   <0,1,2>
            Default: 1
       IV-rate-range: (min,max)
            Range:    <100-6000>
       IV-blood:
            Range: <indicated,not-indicated>
```

ADDITIONAL SLOTS FOR DRUG TREATMENT-

```
  Properties:
       Dosage: <amount in units appropriate for drug>
       Vector: IV
```

Figure 7. Treatment procedure frame organizations.

Each treatment frame also has additional slots for treatment properties that depend upon whether the treatment is IV fluid or atropine (i.e., drug). The properties slots for IV fluid treatment contain information on the number of IV infusion units required, the range of IV infusion rates possible, and whether or not blood transfusions are indicated. The iv-rate-range slot provides practical lower and upper bounds in cc/hr for the administration of fluid for the particular injury. Absolute lower and upper bounds currently are limited by equipment considerations (0 and 6000, respectively). IV-blood is a simple indicator for transfusions based on the average amount of blood loss necessary to produce the severity of shock being treated. This information is used to advise attending medical personnel of the need for a

transfusion since CEMES does not manage blood transfusions. Figure 8 provides an example of a treatment frame for class 3 hemorrhagic shock.

```
Treatment-name:  Class-3-shock-treatment
 Trend-adjustments:
      Unchanged:     (+ 1000)
      Worse:         (+ 1000)
      Much-worse:    (+ 1500)
      Better:        (- 1000)
      Much-better:   (- 1000)
 Properties:
      IV-units-required:  2
      IV-rate-range:      (3000,6000)
      IV-blood:           indicated
```

Figure 8. Class 3 hemorrhagic shock treatment frame.

The properties slots for drug treatments include the dosage as measured in units appropriate for the drug to be administered (which is indicated in the treatment procedure name). The vector slot indicates how the drug is to be administered. At present, atropine is administered through an IV piggyback line. The vector slot is present to allow future iterations of CEMES to include a nebulizer or other means to administer drugs.

The various hardware system components in CEMES also are represented by frames. Unlike the frames for injuries, the hardware frames are independent and do not have relational pointers. Presently, only automated IV fluid and intravenous drug administration units are represented in CEMES.[8] The various biomedical sensor units do not have a representation in CEMES. The sensor units are investigated through simple algorithmic analyses of the data they produce.

Figure 9 shows the frame organizations for the various IV hardware units. As with the treatment frames, there are basic frame slots common to all IV hardware units, and specific slots depending upon whether the unit delivers fluid or a drug. All hardware frames contain a type slot which indicates what the hardware unit delivers. The is-attached slot is an indicator for attachment to the casualty. The is-functioning slot indicates whether the hardware unit is function properly, not functioning

---

[8] An IV administration unit is assumed to consist of an IV bag containing appropriate solution (usually Ringer's lactate), tubing and needle for fluid delivery, and an automated pump that generates fluid flow at the rate determined by CEMES.

```
BASIC FRAME-

  Type:
       Range: <IV,atropine>
  Is-attached:
       Range:   <yes,no>
       Default: no
  Is-functioning:
       Range:  <yes,no,problem>
       Default: no
  Absolute-start-time: <cycle-number>


ADDITIONAL SLOTS FOR IV FLUID UNIT HARDWARE-

  Relative-start-time: <cycle-number>
  Number-of-renewals:  <number>
  Fluid-remaining-this-bag:
       Range: <0-1000>
  Current-administration-rate:
       Range: <0-3000>


ADDITIONAL SLOTS FOR IV DRUG TREATMENT HARDWARE-

  Amount-remaining:
       Range: <0-1000>
  Mixture-ratio: <number>
  Current-dosage: <number in appropriate units>
```

Figure 9. Treatment hardware frame organizations.

(e.g., out of fluid), or if there is a problem (e.g., actual fluid flow does not match signalled fluid flow, indicating a possible blockage). The absolute start time slot provides the cycle number when the hardware unit was attached successfully to the casualty.

The specific slots for IV fluid delivery hardware include a relative-start-time slot which is the cycle number when the current IV fluid bag was started. The number-of-renewals slot is the number of IV fluid bags delivered prior to the current bag. The fluid-remaining slot holds the amount of fluid left in the current bag, while the current-administration-rate slot holds the current delivery rate in cc/hr for the IV fluid unit (which is not necessarily equal to the total infusion rate if more than one IV fluid unit is attached to the casualty).

The specific slots for intravenous drug delivery include a current-dosage slot which holds the amount of the drug being delivered on any given cycle in units appropriate for that drug (mg

for atropine). The other slots are specific to the intravenous delivery of a drug. Generally, drugs given this way are distributed in premixed IV fluid bags at a specific ratio. For example, an atropine bag may have 10mg of atropine mixed for every 100cc of fluid. Therefore, delivery of 1mg atropine requires intravenous injection of 10cc of atropine bag fluid. The mixture-ratio slot provides the ratio of drug to fluid and is used for calculating how much fluid must be delivered to obtain the required dose. The amount-remaining slot holds the fluid remaining in the drug mixture bag.

Inference procedures

The inference procedures used by the CEMES' expert system are different in both technique and use from the process control loop. Whereas the process control loop governs the order of task completions in CEMES, the inference procedures govern the reasoning of the various subsystems with respect to diagnoses, trends, etc.

The basic inference technique used in CEMES is a check and eliminate heuristic which has been outlined in flow-chart form in Figure 10.[9] The method works as follows. Initially, all injury frames are entered into a current candidate list. The heuristic starts by selecting a vital sign based on its importance for diagnosing shock or contamination.[10] The current value of the selected vital sign is compared with the range constraints for that vital sign as given in the diagnostics property list of each injury frame in the current candidate list. If the current vital sign value does <u>not</u> fall within the acceptable range, then that injury frame candidate is marked for elimination from the current candidate list (i.e., the frame must <u>fail</u> to be marked for elimination. If it has no constraints for the vital sign, then it will remain a candidate.) After all injury frames in the current candidate list have been checked with respect to the selected vital sign, those injury frames marked for elimination are removed from the current candidate list. If only one injury frame is left, it then becomes the diagnosis. If all current injury frames in the candidate list are marked for elimination, then the

---

[9] This elimination scheme is adapted from a theory of choice first described by Tversky (1972). He referred to it as the "elimination by aspects" choice process. A complete theoretical treatment of various choice and selection processes can be found in Landon (1983).

[10] The ordering for shock is systolic blood pressure, pulse pressure (the difference between systolic and diastolic blood pressure), pulse, and respiration rate. Pulse is the only sign checked for contamination.

one with the greatest severity index becomes the diagnosis. If more than one injury frame remains after those marked for elimination have been removed from the current candidate list, another vital sign is selected for examination and the elimination process is repeated on the reduced candidate list. If there remains more than one injury frame in the candidate list after all vital signs have been checked, then the injury frame with the greatest severity index becomes the diagnosis.

The check and eliminate method of inference was selected due to its capability for completing a diagnosis during degraded mode operation (i.e., inference with incomplete data, as opposed to incomplete knowledge). For example, any prototypical rule-based system using chaining would collapse as less and less information was available in the database (i.e., matches would be impossible to obtain or the knowledge base would have been expanded to in-

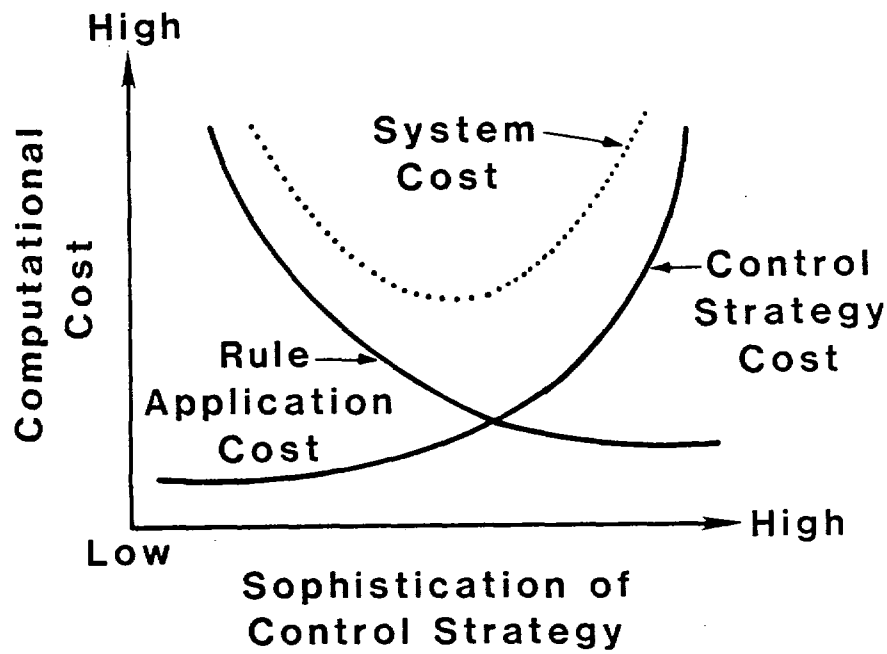

Figure 10. Check and eliminate inference procedure.

clude rules accounting for all possible combinations of the available vital sign data). The elimination technique has both an advantage of speed and a robustness when various vital sign data are unavailable. That is, when a vital sign's data is marked as invalid it effectively does not exist and is removed from the vital sign list prior to entering the check and eliminate inference procedure (a very simple thing to do). Therefore, the missing vital sign has no bearing on the diagnosis because it is never checked. Conversely, if the most important vital sign data are available and the diagnostic constraints are mutually exclusive across most injury frames, elimination down to a single candidate will be fairly quick and avoid all sorts of confirmatory procedures and mechanisms.

A second, and critical, point concerns the concurrent diagnosis of shock and chemical contamination. Chemical contamination, of itself, cannot be sensed by CEMES but must be signalled as a possibility by the attending medic or physician. The principal vital sign used in determining the severity of contamination is pulse. However, the effect of contamination is to depress pulse, a contraindication of shock. Therefore, pulse should not be used to diagnose shock under the presence of contamination, effectively causing a degraded mode diagnosis for shock. This is accomplished by removing pulse from the vital sign list when shock is diagnosed. When contamination is diagnosed, only pulse is entered in the vital sign list.

In addition to diagnostic inference, CEMES also incorporates trend inference mechanisms to determine the current diagnostic trend. Recall there are three directions (improving, deteriorating, and unchanging) and two magnitudes (catastrophic and gradual) for a trend outcome. The conditions for trend direction are provided by the current injury frame in terms of properties and relations (Figure 5).

The trend inference generally is straightforward. The previous cycle's diagnosis (kept by the trend object) is checked to see if it is the same as the current active diagnosis. If it is, then the vital signs are checked by the elimination method described above against the trend property lists to determine direction. It is generally the case that each vital sign has opposite indications for an improving or deteriorating direction, and so the general direction can be determined quickly. However, medical requirements sometimes dictate that more than one sign (usually at least systolic blood pressure and pulse) satisfy the trend constraints before a direction is confirmed. In such cases, the elimination inference procedure continues until the required number of constraints are failed by either the improving or deteriorating direction. If both the improving and deteriorating directions fail, then the trend direction defaults to unchanging.

Trend magnitude is determined through straightforward algorithmic techniques accomplished concurrently with directionality checking. Catastrophic magnitude is indicated if the current vital sign value deviates from the previous vital sign value or the median of the previous five values by 10 or more. Gradual magnitude is indicated by a strict increasing or decreasing ordering of the vital sign values over the last five cycles if such an ordering does not meet the catastrophic magnitude constraints. If the direction indicated is unchanged, then magnitude is irrelevant. Conversely, if neither catastrophic nor gradual magnitude is found (as indicated by failure to meet the algorithmic requirements), then the direction is unchanged.

In the cases where the previous (i.e., last cycle's) diagnosis is not the same as the current injury frame, the previous injury frame is checked against the trend relations of the current active diagnosis. If a match is found, then the trend is established by which category of match was obtained (i.e., worse-than indicates a gradual deterioration, much-worse-than indicates a catastrophic deterioration, etc. See Figure 5). If a match is not found, then the trend defaults to unchanged. That is, if the current diagnosis has no relation with the previous cycle's diagnosis, then there is no trend. A trend cannot be established in a single cycle.

The final type of inference made by CEMES is the selection of a treatment. This consists of selection of an appropriate IV fluid infusion rate if IV fluid treatment is indicated by the active treatment model frame and/or an atropine dose. The selection of an IV infusion rate has three principal steps. First, the rate is set to at least the minimum required by the treatment model (given by the iv-rate-range slot). Next, this rate is adjusted up or down according to the trend adjustment given by the slot corresponding to the current trend. The rate is then reset to the minimum or to the maximum if the adjustments cause it to exceed those bounds. Note that the absolute maximum for the system is 6000cc/hr, while the absolute minimum is 0 if no IV fluid infusion units are attached, or 100cc/hr if one is attached (to maintain an open line).

Recall that via the process control loop, a final IV infusion rate is determined after an effectors analysis by the logistics subsystem. If the treatment subsystem has requested a positive IV infusion rate, the current treatment model frame is checked to see how many IV units are required (i.e., the iv-units-required slot). The IV unit hardware frames then are checked to see if the required units are attached and functioning. If they are not attached, a message is printed on the graphics display informing the medic or physician the casualty requires an IV line to be established for treatment. If they are attached but malfunctioning or out of fluid, appropriate messages are displayed. Depending upon the outcome of the effectors analysis, the logistics

subsystem provides an appropriate message for the treatment subsystem, which then readjusts the IV infusion rate if necessary.

Any atropine dosage that might be required is selected in a more straightforward fashion. The treatment model frames for contamination simply state the dose required. However, the nature of intravenous atropine delivery requires that it be cycled in five minute intervals. That is, consecutive doses of atropine must be administered at least five minutes apart. The treatment subsystem maintains timing mechanisms and cues to properly effect this cycle.

The CEMES front-end

The process control loop and subsystem tasking

The front-end portion of the CEMES system resides on the HP 9000 minicomputer. The front-end is responsible for controlling or simulating all data input and output for the expert system portion on the Symbolics LISP machine.[11] As noted in the previous section "CEMES general design" and Figure 3a, the front-end primarily is composed of the sensor and effector subsystems along with some independent programs used to augment CEMES front-end functions. These independent programs consist of the Master Control Program, the Graphics Display Generation and Control Program, and the Communications and File Transfer Control Program.[12] The function of each of these programs is suggested by their respective names, although more detailed explanations will be given later. As in the expert system portion of CEMES, the front-end is governed by a process control loop that coordinates the various programs that comprise the front-end.

The CEMES front-end process control loop, diagrammed in Figure 11, is implemented within the Communications and File Transfer Program. This program cycles in response to signals received from the CEMES expert system (i.e., in one minute intervals). The signals function as either data requests or information updates. A data request signal indicates that current front-end blackboard information should be transmitted to the expert system for processing (i.e., the start of a new cycle). These data consist of current vital signs, sensor hardware status messages, and effector hardware status messages. Information updates contain graphics display updates and/or effector control information. Data request signals always precede information updates (i.e., consistent with the expert system process control loop. See Figure 4.)

The front-end process control loop has five major steps (Figure 11). Upon receiving a data request signal from the expert sys-

---

[11] This section is intended to cover the function of the front-end subsystems and programs. It is not intended to serve the dual purpose of a user's manual. However, a careful reading of this section should provide enough information to operate CEMES so long as one is familiar with the HP 9000 and Symbolics 3640 computers.

[12] Since the sensor and effector subsystems also have their own independent programs, the front-end in actuality consists of five separate programs, not including the various simulation hardware.

Wait for data request from expert system

Obtain current vital signs, sensor, and effector status messages from the HP blackboard

Transmit new data to expert system

Wait for update information to be sent by the expert system

Post new information on the HP blackboard

Generate appropriate signals to inform other front-end programs that the HP blackboard information has changed

Recycle

Figure 11. CEMES front-end process control loop.

tem, the Communications and File Transfer Control program obtains the necessary data from the HP blackboard. These data are encoded into an ASCII file for transmission to the expert system on the Symbolics. The file is then dispatched along a RS232 connection to the Symbolics where the expert system decodes the file and processes the new information as discussed in the previous section "The CEMES expert system."

After sending the requested data, the Communications and File Transfer Control Program enters a wait state until update information is received from the expert system. When the update information is received, the Communications and File Transfer Control Program enters the new information on the HP blackboard. Appropriate messages are sent to the other front-end programs to signal that the blackboard has changed. The Communications and File Transfer Program then enters another waiting state until the expert system restarts the front-end process control loop by sending another request for new data.

It should be noted that the front-end process control loop is not a complete description of the operation of the CEMES front-end, but is primarily the interface mechanism between CEMES' two major components (i.e., the expert system and the front-end).

The other front-end component subsystems and programs operate independently (and sometimes continuously). These other front-end components will be individually described below.

The sensor subsystem

The front-end sensor subsystem consists of the Sensor Data Processing Program, various hardware interfaces within the HP 6942A multiprogrammer, and the vital sign and casualty simulation equipment. A diagram showing the general connections and organization of the sensor simulation equipment is given in Figure 12.

The sensor subsystem is one of two ways that front-end sensor-based information can be obtained by CEMES. The second way is through a menu-based program that will be described in detail in the following section "The master control program." The sensor subsystem simulates a real-time environment, whereas the menu-driven program provides a more controlled manner of entering data. The system operator is queried when CEMES is first activated as to which method of data acquisition is desired. Of course, in an operational CEMES all data will be acquired automatically through the sensor subsystem.

The principal function of the sensor subsystem is to provide real-time biomedical signals and data to simulate the physiology of a casualty. Since operational testing of CEMES isn't possible, the sensor subsystem includes various off-the-shelf patient simulators (normally used to provide test signals for hospital patient monitoring equipment) and some custom-made equipment that enables physiological conditions to be simulated as though noninvasive sensors were taking real data from an actual casualty. The signals provided by the casualty simulation equipment are digitized using appropriate hardware in the HP 6942A multiprogrammer. The Sensor Data Processing Program converts the digitized signals to numerical form, conducts a simple analysis of the data's validity, and enters the resulting values in the appropriate portion of the HP blackboard.

Signal data is provided to the sensor subsystem through either the patient simulators or the signal controller box (Figure 13). Ranges and values of the various vital signs are generally restricted on the patient simulators. Therefore, the signal controller provides a means for switching that equipment out of the sensor sampling loop and adjusting the vital signs using the various dials on the signal controller box. When the controller box switches are set to internal, vital signs are adjusted using the dials on the controller box (as appropriately labeled). When

1. LOVE(JOHN,MARY)

JOHN LOVES MARY. LOVE IS A PREDICATE SYMBOL.

2. SISTER(SUE,KATHY)

KATHY IS SUE'S SISTER. SISTER IS A PREDICATE SYMBOL.

3. MARRIED[FATHER(BOBBY),MOTHER(BOBBY)]

BOBBY'S FATHER IS MARRIED TO BOBBY'S MOTHER. FATHER AND MOTHER ARE FUNCTION SYMBOLS. MARRIED IS A TWO-ARGUMENT PREDICATE SYMBOL. AN ALTERNATE INTERPRETATION IS "JOHN IS MARRIED TO MARY."

4. MARRIED[FATHER(SUE),FATHER(KATHY)]

SUE'S FATHER IS MARRIED TO KATHY'S FATHER.

5. CHILD(BOBBY)

BOBBY IS A CHILD. CHILD IS A SINGLE ARGUMENT PREDICATE SYMBOL.

Figure 12. Sensor subsystem equipment diagram.

1. LIVES(JOHN,HOUSE) $\wedge$ COLOR(HOUSE,BROWN)

JOHN LIVES IN A BROWN HOUSE.

2. LOCATION(HOUSE,MAPLE) $\vee$ LOCATION(HOUSE,OAK)

THE HOUSE IS ON MAPLE OR OAK STREET.

3. $\sim$ SISTER(MARY,SUE)

MARY AND SUE ARE NOT SISTERS.

4. OWNS(JOHN,HOUSE) $\longrightarrow$ COLOR(HOUSE,BROWN)

IF JOHN OWNS THE HOUSE, THEN IT IS BROWN.

5. MARRIED(JOHN,MARY) $\equiv$ LOVE(JOHN,MARY)

JOHN IS MARRIED TO MARY IS EQUIVALENT TO JOHN LOVES MARY.

6. FATHER(BOBBY) = FATHER(SUE)

BOBBY AND SUE HAVE THE SAME FATHER.

Figure 13. Sensor subsystem casualty simulation equipment.

switched to external, vital signs are obtained from the various patient simulators. In the latter case, the data are first routed through Tektronix patient monitors as a first step in signal analysis. In either case, the signals are digitized through the multiprogrammer.

The Sensor Data Processing Program obtains vital sign signal samples from the multiprogrammer every 2 seconds. These samples are displayed on the operator interface simulation screen (i.e., not the graphic display) so that the system operator can easily track the vital sign values being entered. The 2-second interval provides a substantially finer sampling resolution than the 1-minute processing cycle (which, in turn, is a finer resolution than the normal time course of human physiological change). The 2-second sampling rate provides a sufficient number of samples for an analysis of the sensor data for spikes, excessive variability, and other indicators of sensor malfunction. When new data is requested by the expert system (i.e., step one in the front-end process control loop), the Sensor Data Processing Program analyzes the vital sign data samples taken in the past cycle to determine if the various sensors appear to be functioning properly. If so, the new vital sign values are entered on the HP blackboard (which causes their display on the CEMES graphic display). Otherwise, appropriate messages are provided indicating that a sensor has malfunctioned. The algorithms and signal processing accomplished by the Sensor Data Processing Program are covered in Landon (1988b).

It should be noted that when first starting the CEMES system, the system operator is queried as to whether the Sensor Data Processing Program will conduct an analysis of the vital sign data samples or not. Unless one is aware of how the algorithms work with regards to flagging a malfunctioning sensor, the program may interpret fluctuations in the vital sign data due to a system operator's inappropriate adjustment of vital sign values as a malfunctioning sensor. There is no way to avoid this pitfall other than not using the analysis algorithms of the Sensor Data Processing Program. That is, a full-fledged test scenario should be constructed on paper before running a complete test of CEMES with all options active.

The effector subsystem

The front-end effector subsystem consists of the Treatment Hardware Control Program, various hardware interfaces within the HP 6942A multiprogrammer, and the IV pump simulation equipment. A diagram showing the general connections and organization of the effector simulation equipment is given in Figure 14.

The principal function of the effector subsystem is to simulate the delivery of IV fluid infusion and drug treatments to the

casualty. The effector subsystem includes various off-the-shelf industrial pumps, actual IV tubing and needles, and fluid containers that are used to simulate the delivery of IV fluid (Figure 15). The Treatment Hardware Control Program converts the treatment regimen messages received from the expert system to control signals that govern the fluid pumping rates of the IV infusion pump simulators.

The treatment regimen messages sent from the expert system consist of an IV fluid infusion rate (in cc/hr) and an atropine dose (in cc, if required). The Treatment Hardware Control Program converts the IV infusion rate to appropriate control signals for the HP 6942A multiprogrammer digital-to-analog control cards, which in turn convert the control signals to steady-state current which governs the pumping rate of the FMI QA600 pumps used to simulate the automatic infusion of fluids.

Note that one pump is used for IV fluid delivery and one for atropine piggyback drug infusion (Figure 14). Due to equipment limitations, a single pump is used with a two-place manifold to simulate the two IV infusion units assumed by the expert system

1. $\exists x$: MARRIED(x,JOHN)

THERE EXISTS SOMEONE X SUCH THAT X IS MARRIED TO JOHN.

2. $\forall y$: MEMBER(y,SMITH FAMILY)

FOR ALL PEOPLE Y, Y IS A MEMBER OF THE SMITH FAMILY.

3. $\exists x$: MOTHER(x,MARY) $\wedge$ SISTER(x,SUE)

THERE EXISTS SOMEONE X SUCH THAT X'S MOTHER IS MARY AND X'S SISTER IS SUE.

4. $\exists x \exists y$: LOVE(x,y)

THERE EXISTS A PERSON X AND A PERSON Y SUCH THAT X LOVES Y.

Figure 14. Effector subsystem equipment diagram.

1. **Every city has a dogcatcher who has been bitten by every dog in town.**

$$(\forall x)\{CITY(x) \rightarrow (\exists y)\{DOGCATCHER(x,y) \wedge (\forall z)\{[DOG(z) \wedge LIVES\text{-}IN(x,z)] \rightarrow BIT(y,z)\}\}\}$$

2. **All blocks on top of blocks that have been moved or that are attached to blocks that have been moved have also been moved.**

$$(\forall x)(\forall y)\{\{BLOCK(x) \wedge BLOCK(y) \wedge [ONTOP(x,y) \vee ATTACHED(x,y,)]\} \vee \{\rightarrow MOVED(x)\}\}$$

Figure 15. Effector subsystem IV infusion simulation equipment.

to be available. However, the expert system operates as though there were two independent IV infusion units with independent fluid bags (even though the amount fluid is essentially limitless in this prototype). The Treatment Hardware Control Program turns the atropine pump on and off as appropriate to deliver the required amount of simulated atropine fluid mixture.

The simulation of IVs also involves signalling when infusion units are attached, when fluid bags are replaced, and other hands-on aspects of IV administration. Explanations of these additional effector-oriented simulation requirements will be provided in the following section "The master control program."

The graphic display

The graphic display is generated and controlled by the Graphics Display Generation and Control Program. The graphic display provides a means for visually displaying the status of CEMES and its various operations from cycle to cycle. The task of the Graphics Display Generation and Control Program is to maintain congruency between the information in the HP blackboard and the information on the graphic display. An example of the graphic display is provided in Figure 16. It should be noted a display of this complexity may or may not be included in a field operational CEMES system. This particular graphic display design was implemented to provide all the necessary information to aid in CEMES' design

and testing. There are five major areas of the display, each set off from the other and suitably labeled.

The vital signs display area contains the current vital sign data, which is defined as the data last sent to the expert system (i.e., it may not be the most recent data, which is defined as the data from the last sample taken by the sensor subsystem). Note that provisions have been made on the display for some vital signs that aren't yet being used by the expert system (see the following section "Future developmental directions").

The elapsed time display area provides several time indicators. The principal indicator is in large type and provides the amount of time the casualty has been attached to the system (i.e., a relative measure). Below that are indicators for when the casualty was attached to the system (the start time, an absolute measure) and for when the display was last updated (the last display update, an absolute measure). Note that the last display update time is not always to the last cycle time. The graphics

1. $\sim(\sim X) \equiv X$
2. de Morgan's Laws:
   $\sim(X \wedge Y) \equiv \sim X \vee \sim Y$
   $\sim(X \vee Y) \equiv \sim X \wedge \sim Y$
3. Distributive Law:
   $Y \wedge (X \vee Z) \equiv (Y \wedge X) \vee (Y \wedge Z)$
4. Commutative Law:
   $Y \wedge X \equiv X \wedge Y$
5. Contrapositive Law:
   $Y \rightarrow X \equiv \sim X \rightarrow \sim Y$
6. $\sim(\exists X)P(X) \equiv (\forall X)[\sim P(X)]$
7. $(\forall X)P(X) \equiv (\forall Y)P(Y)$

Figure 16. CEMES graphic display example.

display sometimes will be updated in response to an operator generated signal of some external event that occurs independently of the normal cycle.

The system status display area is where the expert system displays various messages having to do with the casualty's diagnosis, the administered treatment regimen (because the effector subsystem may not have the capability for delivering the pre-

ferred regimen), logistical indicators, and any additional messages deemed necessary. These four classes of messages are separated and displayed under appropriate labels that define display subareas within the system status area. The various messages are color coded white, green, yellow, or red depending upon the type of message. The default display color is white, with system OK messages in green, cautionary or advisory messages in yellow, and severe or warning messages in red. Advisory and warning messages also are accompanied by additional visual cues in the form of a header (as in the "ALERT" header shown in the Figure 16 example) and auditory cues with differing frequencies and temporal characteristics.

The hardware status display area provides a pictorial display of the location and status of the various sensor and effector units that have been attached to the casualty. The icons and labels for each hardware item are color coded to provide visual cues as to their status. Green indicates the hardware is OK and functioning properly. Yellow indicates a problem or a malfunction. Red indicates the hardware item is not functioning (for whatever reason).

The hardware status display area in the example (Figure 14) shows various devices that serve as examples for what could be included in an operational front-end.[13] An automated BP cuff is attached to provide blood pressure measurements. The PMC label represents a personal monitor and communicator which provides heart rate and respiration rate. This particular casualty has had two IV units attached, one of which is getting low on fluid. He also has had an atropine piggyback line established.

The last display area is the trend graph at the top of the display. This graph provides a chart upon which the various vital sign data can be plotted for a visual indication of how those signs have changed across time. The example in Figure 16 shows systolic blood pressure and heart rate. The values plotted are absolute values, with the scale shown at the left of the graph. The intermittent vertical lines represent 10 minute intervals in real-time. At present, the Graphics Display Generation and Control Program only can display systolic blood pressure and heart rate on the trend graph.

Note the trend graph has room to display 1 hour's worth of data. This shows the graph's particular configuration for the first hour of operation. After the first hour, the horizontal scale on

---

[13] The example in Figure 16 is <u>not</u> meant to indicate that all of the equipment shown is either necessary or will be assumed to part of an operational CEMES front-end. There are both scientific and practical questions that must be addressed with regard to how to noninvasively monitor certain physiological signs.

the graph condenses to represent 2 hours' worth of data (i.e., the number of vertical lines doubles). The last hour's data is redrawn on the new scale with new data being graphed on the end of the previous hour. That is, there is always as much data as is available, or at least 1 hour's worth of data with the new data being added on as received.

The trend graph area also displays the total amount of IV fluid that has been administered to the casualty along with the total amount of atropine. This is to provide additional information for a physician or medic should hands-on interruption of the system be required.

The master control program

The principal program for interacting with CEMES is the Master Control Program shown on Figure 3a. This program provides all the various menu-driven capabilities for control and interaction through the front-end. An organizational chart of the various menus available in the Master Control Program is provided in Figure 17. The specific menus themselves are shown in Figure 18 exactly as they appear on the console CRT. The menus serve as labels for the softkeys provided on the HP 9000 keyboard. A push of the appropriate softkey initiates the particular action indicated by the key's label. An explanation of the Master Control Program will proceed through an explanation of what can be done within each menu.[14]

The main menu provides a starting point of selecting the particular activity to be accomplished. The "System Startup" selection begins execution of the front-end programs (as opposed to loading and running the Master Control Program which requires some know-

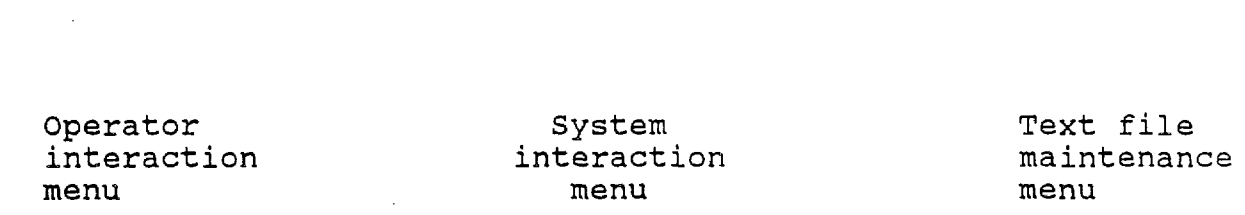

Figure 17. Master Control Program menu hierarchy.

[14] To reiterate, this discussion is not intended as a user's or instructional manual for the operation of the CEMES front-end, even though the explanation of the various menu selections of the Master Control Program will provide a basic knowledge of how to operate CEMES from the front-end.

ledge of the HP 9000 minicomputer). When the "System Startup" selection is made, the Master Control Program executes a series of functions that boots the remainder of the front-end systems. When appropriate, the booting functions ask the system operator if menu driven vital sign input is desired. Answering "No" initiates automatic sampling as discussed in the previous section "The sensor subsystem." If automatic sampling is requested, the booting functions will also ask if the sensor functionality checks should be activated. The booting functions will then complete the front-end initialization and prepare CEMES for operation. Selecting the "System Shutdown" option on the Main menu will then stop operation of the front-end programs and reset the HP 9000 for normal computer operations.[15]

The "File Backup" option on the Main menu provides a means for automatically generating floppy disk backups of all the front-end programs and files that normally reside on the HP 9000's internal hard disk. A full backup requires three properly formatted 5.25-inch floppy disks, each of which is inserted into the internal floppy disk drive on cues provided by the backup program. The backup program returns to the main menu upon completion. The last three selections on the main menu provide branches to the other menus of the Master Control Program.

The main menu "Txt_file Maint" selection branches to the text file maintenance menu (Figure 18). This menu is used to control operations with respect to the four text files that are part of the front-end blackboard (see Figure 3a). These four text files contain the various text messages that appear in the system status portion of the graphic display. The expert system signals the display of the various messages in the four subareas of the system status display area through appropriate codes that are transmitted to the front-end on each cycle. The Graphics Display Generation and Control Program interprets the various codes, retrieves the proper messages from the text files, and generates the appropriate graphics for the display.[16]

---

[15] Note that to setup the computers for CEMES operation requires that the Master Control Program first be loaded and run on the HP9000 (<u>without</u> selecting the "System Startup" option), then the expert system be started on the Symbolics 3640, and lastly the "System Startup" option be selected from the Main menu of the Master Control Program.

[16] The text message codes are the actual information stored in the blackboard file after being parsed from the updated information file by the Communications and File Transfer Control Program. That is, the <u>only</u> place where the text messages appear in readable form is on the graphic display or in a hardcopy dump of the text file.

Text file maintenance operations proceed by first selecting a file to work on (the "Select File" choice on the menu), and then completing whatever actions are desired. The "Add Text" selection branches to a routine for adding new text messages to the file. The "Output Hardcopy" selection produces a listing of all text messages currently in the file on the internal thermal printer of the HP 9000. The "Change Text" selection branches to a routine allowing changes to be made to existing text messages.

As can be inferred from the names of the four text files (Figure 3a), each corresponds to messages that are displayed in the corresponding subarea of the system status display area.

MAIN MENU:

System Startup	System Shutdown	File Backup	Txt_file Maint	System Interact	Not Used	Not Used	Cemes Demo

TEXT FILE MAINTENANCE MENU:

Select File	Add Text	Output Hardcopy	Change Text	Not Used	Not Used	Not Used	Main Menu

DEMONSTRATION MENU:

Demo Setup	Demo Shutdown	Create Demo	Change Demo	Hardcopy Demo	Not Used	Start Demo	Main Menu

SYSTEM INTERACTION MENU:

Change Blckbrd	Cause Events	Suspend Opertn	Output Hardcopy	Not Used	Not Used	Not Used	Main Menu

CHANGE BLACKBOARD MENU:

Diagnose Treat	Logist Mess	Treat Hardware	Sensor Hardware	Not Used	Vital Signs	DO IT	Interact Menu

Figure 18. Master Control Program menus.

Each text file can contain up to 400 different messages with no more than 52 characters per message (including spaces and punctuation). The operation of the expert system and system programmer determine the types of messages entered into each file.

The "System Interact" selection on the main menu branches to the system interaction menu (Figure 18). The system interaction menu is used when menu-driven control of the sensor and effector subsystems is desired during a normal test run of CEMES. The "Vital Signs" selection provides for menu-driven input of vital sign values to the front-end blackboard. This is used in lieu of the automatic sampling of vital signs from the sensor subsystem. The program will not allow you to take this selection if automatic sampling was requested during the boot-up operation.

The "Treat Hard" and "Sensor Hard" selections on the System Interaction menu provide for a means to artificially signal a malfunction of some front-end piece of equipment. Only strict malfunctions can be signalled, as other problems are a domain of analysis for the expert system. The "Sensor Hard" selection will also let the operator signal that a particular sensor is attached or unattached (note that an unattached sensor cannot provide data, and the expert system will react accordingly).

The "DO IT" selection is taken when the changes to the front-end made through the "Vital Signs," "Treat Hard," and "Sensor Hard" selections are complete. That is, no entry is permanent and entered on the front-end blackboard until the "DO IT" selection is made. The desired changes will not show up on the graphic display until "DO IT" is selected. This is primarily a safety mechanism to prevent unwanted changes or mistakes.

The "Output Hardcopy" selection provides either a 'snapshot' printed output on the internal thermal printer of the data currently in the front-end blackboard, or a color graphics plot of the current graphic display screen on an HP 7475A six-pen plotter (see Appendix A) that's attached to the HP 9000. The plotted output is drawn by a special program that's loaded and run when a plotted output is desired. It takes several minutes and runs independently of CEMES once started. It should be noted that once the plot is started, it must finish before another can be started. That is, plots of successive graphic display screens are not possible.

The Operator Interaction menu, entered by selecting "Operator menu" on the Main menu or System Interaction menu, provides a means for simulating certain actions an attending medic or physician would have to complete at CEMES request in an operaional environment. Since an actual casualty cannot be attached to the system for testing, this menu allows actions such as IV attachment, bag replacement, etc. to be simulated. These menu selections are fairly self-explanatory.

The "Iv hookup" selections signal that the appropriate IV unit has been attached to the casualty as requested by CEMES. Unit 1 should always be attached before unit 2. "IV bag replaced" signals that an empty IV bag has been replaced with a full bag as requested by CEMES. "IV fluid" increase or decrease will change the current IV infusion rate by 250 cc/hr in the signalled direction. This change will be independent of the rate established by the expert system. These changes essentially are overrides to the rate established by the expert system and should be used with extreme caution. The "Atrop" push and disable selections provide overrides for atropine delivery. The push causes 1 mg of atropine to be delivered (if the atropine piggyback is functioning) right now. The disable selection inhibits the expert system from delivering atropine. The "Chem cont" selection provides a signal

that chemical agent contamination is present. CEMES has no ability to sense chemical agent presence independently. This selection must be made before CEMES will diagnose for the delivery of atropine. The "Hookup atrop" selection signals that the atropine piggyback has been hooked up to the casualty as requested by CEMES.

"GO" is a special selection used when CEMES is booted on the front-end. After the boot up process, CEMES enters a waiting state. The front-end is operational, but the expert system will wait for the "GO" signal which indicates that the initial vital sign values and front-end hardware configuration has been completed. That is, after CEMES has been booted, you can input initial vital sign values and change the status of various front-end hardware. Selecting "GO" the starts the normal 1-minute cycling of CEMES. CEMES will automatically start cycling after 5 minutes if "GO" is not signalled.

It should be noted that there is no demonstration mode for CEMES at this stage as there was for Phase I. All of the CEMES programs have been designed around the 1-minute cycle time. There is no way to change this cycle time and maintain the integrity of CEMES operation. CEMES is demonstrated by developing appropriate short-term casualty scenarios and running them as tests of the system.

Future developmental directions

Although CEMES has been developed to the point of demonstrating all the essential elements of an automated emergency medicine system, there are several additional aspects that could be designed into the system. As pointed out, one of CEMES' operational requirements was to fit into the continuum-of-care and far-forward care concepts governing the evacuation and treatment of casualties. CEMES meets those requirements in the minimal configuration documented here. However, the concept of CEMES can be extended beyond what was described here.

For example, the graphic display includes provisions for blood gas measurement (partial pressure of oxygen and carbon dioxide) and urine output. These signs can be used to govern artificial respiration and fine-tuning of IV fluid infusion, respectively. Assisted respiration is particularly relevant for the treatment of nerve agent contaminated casualties.

Such medical systems as respirators, foley catheters, etc., while not necessarily appropriate for far-forward operations (although this is an unresolved operational question), can be configured as add-ons to the base CEMES system. That is, the base CEMES system, as described in this report, could be deployed as far-forward as possible to aid in initial trauma and shock care. As the casualty is evacuated, additional medical care modules could be added at various levels in the evacuation. It is quite possible that, at far rear areas, enough modules might be added so that each casualty has his own self-contained critical care facility.

Summary

This report describes the exploratory development of a combat emergency medicine expert system (CEMES). The principal aspects of the design and operation of CEMES have been documented. CEMES can diagnose and simulate IV treatment for all classes of hemorrhagic shock. Additional mechanisms for the diagnosis of chemical agent contamination, atropine treatment for contamination, and degraded mode operation have been included.

Appendix A

Manufacturers' list

Bio-Tek Instruments, Inc.
1 Mill Street
Burlington, VT 05401

Dynatech Nevada, Inc.
2000 Arrowhead Drive
P.O. Box 1925
Carson City, NV 89701

Fluid Metering, Inc.
29 Orchard Street
P.O. Box 179
Oyster Bay, NY 11771

Hewlett-Packard Company
Building 5
4700 Bayou Blvd.
Pensacola, FL 32503

Symbolics, Inc.
Department 803
555 Virginia Road
Concord, MA 01742

Tektronix, Inc.
P.O. Box 500
Beaverton, OR 97077

References

Bellamy, R. R. 1984. The causes of death in conventional land warfare: Implications for combat casualty care. Military medicine. 149: 55-62

Cook, V. W., Jr. 1984. Analysis of the Army medical evacuation support system in forward combat areas. Wright-Patterson Air Force Base, OH: Air Force Institute of Technology. AFIT-GST-OS-84M-6.

Department of the Army. 1978. Health service support in a theater of operations. Washington, DC: Department of the Army. FM 8-10.

Department of the Army. 1982. Operations. Washington, DC: Department of the Army. FM 100-5.

Erman, L. D., and Lessor, V. R. 1975. A multi-level organization for problem solving using many diverse, cooperating sources of knowledge. In: Proceedings of the fourth international joint conference on artificial intelligence.

Hayes-Roth, B. 1985. A blackboard architecture for control. Artificial intelligence. 26: 251-321.

Landon, D. E. 1983. An investigation of decision rules and information processing strategies in preferential choice among single- and multi-attribute alternatives. Doctoral dissertation, Purdue University, West Lafayette, IN.

Landon, D. E. 1986. Concept study of closed-loop medical expert system. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL: USAARL Report No. 86-6.

Landon, D. E. 1987. The combat emergency medicine expert system (CEMES) project phase I report. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL: USAARL Report No. 87-4.

Landon, D. E. 1988a. The combat emergency medicine expert system (CEMES) project phase I report: Program code supplement. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL: USAARL LR-88-18-1-3.

Landon, D. E. 1988b. The combat emergency medicine expert system (CEMES) project phase II report: Program code supplement. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL: USAARL LR-88-20-1-4.

National Research Council. 1983. (National Academy of Science: Committee on Army robotics and artificial intelligence). Applications of robotics and artificial intelligence to reduce risk and improve effectiveness: A study for the United States Army. Washington, DC: National Academy Press.

Robertson, J. T., and Glazier, C. J., Jr. 1985 New methods to improve medical readiness. Army research, development, and acqusition magazine. Jul-Aug: 17-20.

Stefik, M., and Bobrow, D. G. 1986. Object-oriented programming: Themes and variations. AI magazine. 6(4): 40-62.

Tversky, A. 1972. Elimination by aspects: A theory of choice. Psychological review. 79: 2871-299.